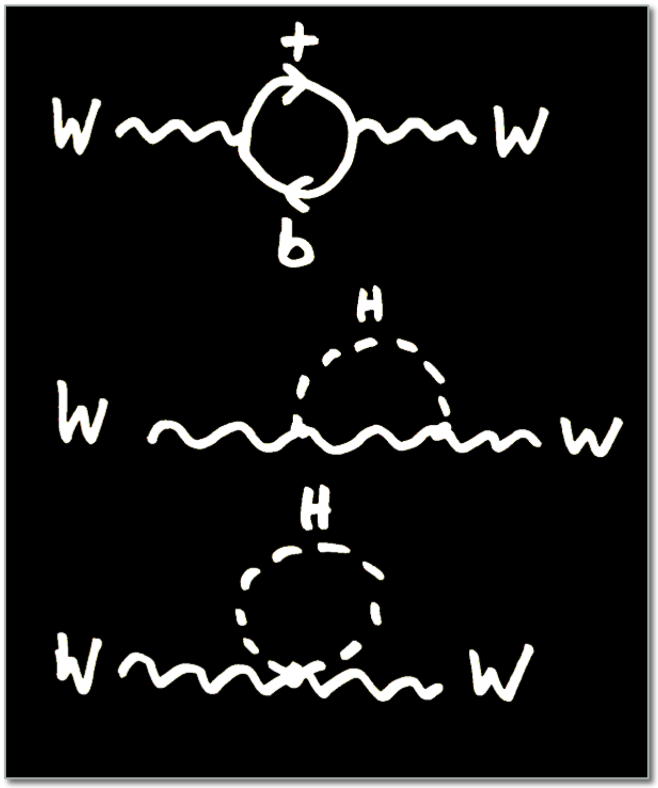
TOP QUARK MASS MEASUREMENTS AT THE LHC

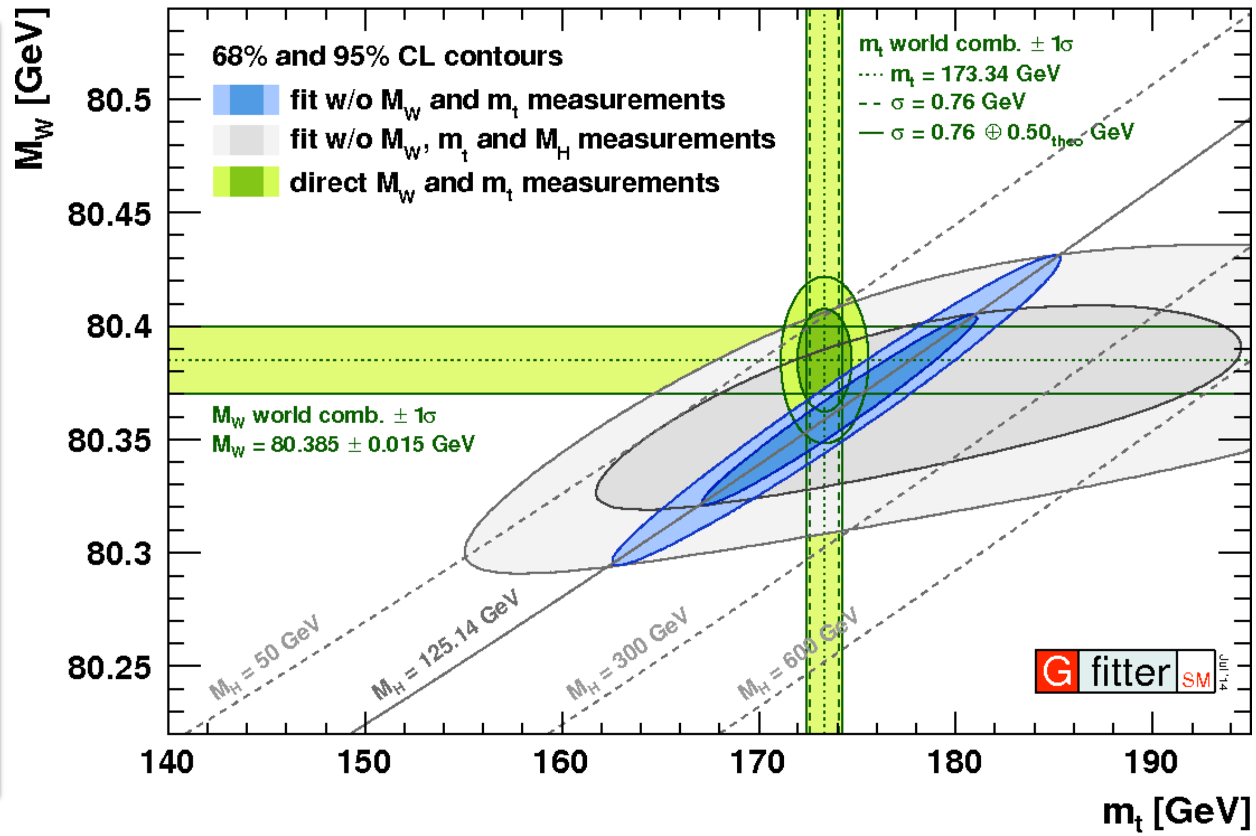
Meenakshi Narain

April 10, 2015

Consistency of the SM

- Higgs, W boson mass and top quark mass





from gfitter.desy.de

Top Quark, Higgs Boson and… our universe

The Top and the Higgs conspire to destroy the universe

Jonathan Leake, Science editor Published: 7 September 2014

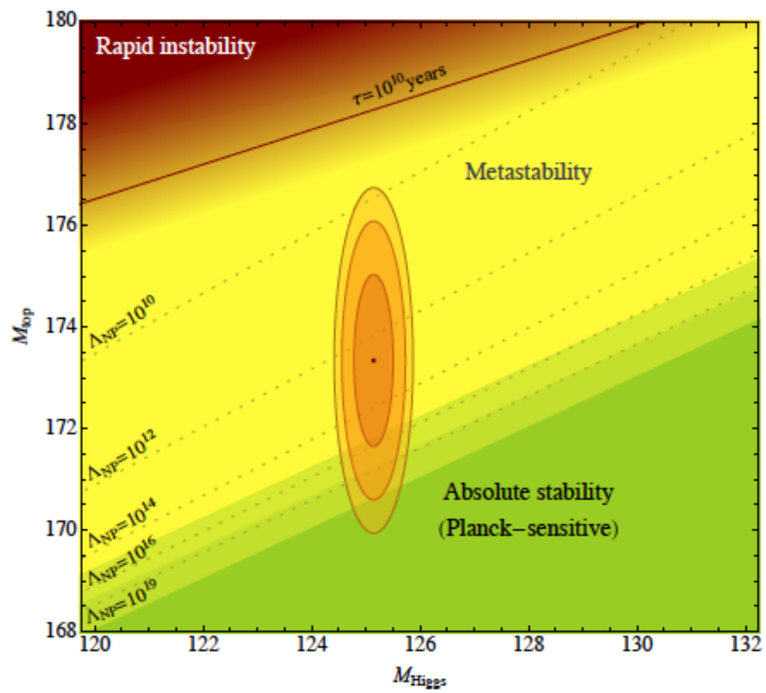
The Nature of the Vacuum

- Stability of the EW vacuum is an important property of the SM
- Measurements of the Higgs boson and top quark masses allow for the first time to infer properties of the very vacuum we live in!
  - A highly fine-tuned situation: the vacuum is on the verge of being either stable or metastable!
  - ~1 GeV in either of the two masses is all it takes to tip the scales
  - stability condition:

$$M_h > 129.6\,\mathrm{GeV} + 2.0(M_t - 173.34\,\mathrm{GeV}) - 0.5\,\mathrm{GeV}\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.3\,\mathrm{GeV}$$

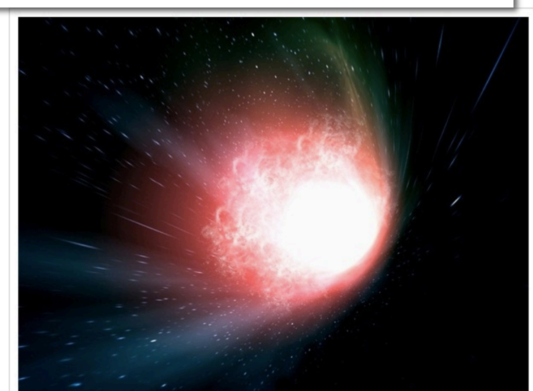
- Are statements about stability independent of the nature of the new physics ??

arxiv:1408.0292
arXiv:1205.6497
arXiv:1307.3536
arXiv:1407.2682
CMS-PAS-TOP-14-015



Will our universe end in a 'big slurp'?

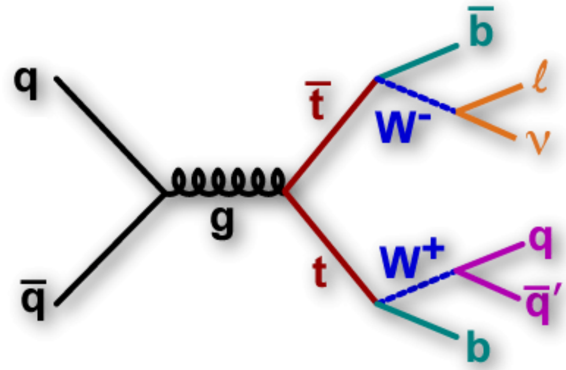
nbcnews.com



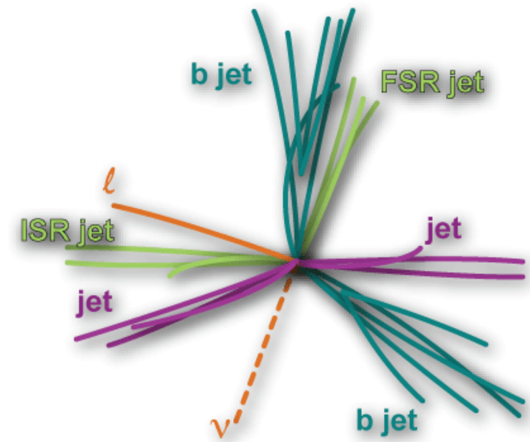
Top quark mass measurement

- Challenges and solutions:

from theory…



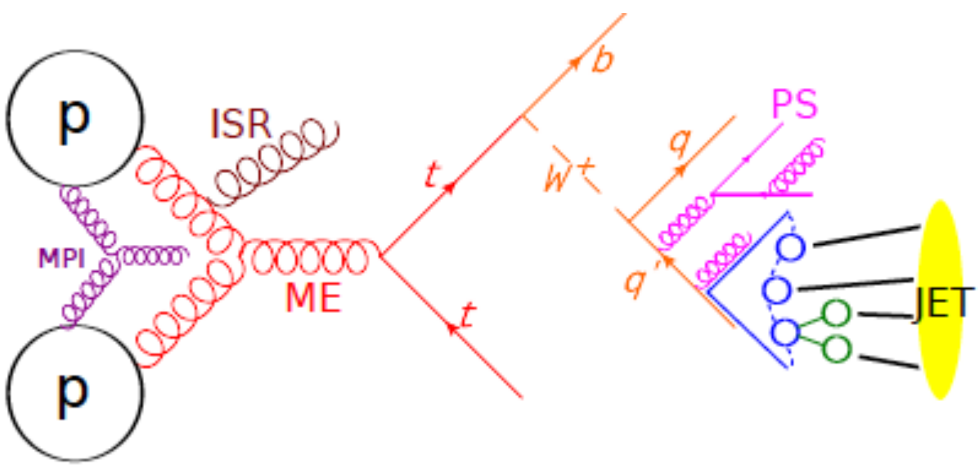
to reality….



- Jet energy scale:
  - "in-situ" JES by using the constraint from hadronic W mass, can be done in l+jets and all hadronic channels, not in di-lepton channel alone.
  - Also look at quantities insensitive to JES, e.g. lepton p_T.
- Jet-parton assignment:
  - b-jet ID helps to reduce the number of permutations.
  - Kinematic fitter to pick up the permutation(s) with best X^2

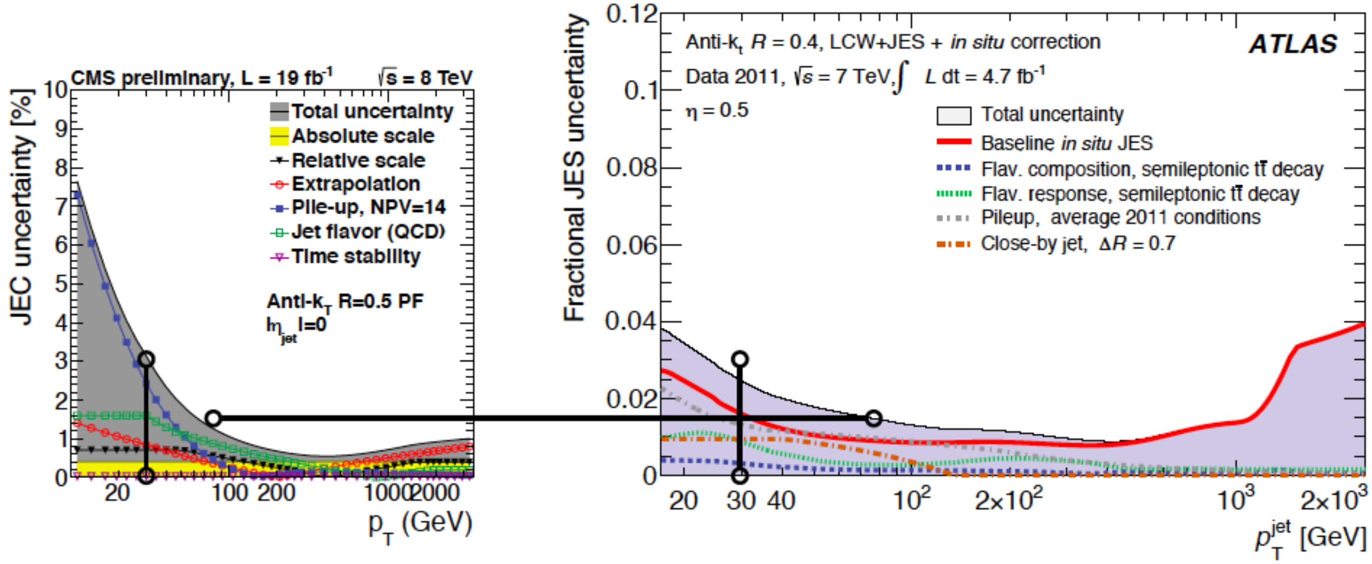
Measuring the top quark mass

- Typical modeling uncertainties in top mass measurements
- Radiation
  - ISR jets from ME generator, additional radiation from PS
  - Vary renormalization scales Λ or for running α_s
  - ATLAS: analyze LO generator AcerMC/Pythia using the P2011C tune. Tunable parameters that control the parton shower strength are varied up and down (in a range compatible with observed tt events with additional jets).
- Hadronization
  - Vary fragmentation functions, decay fractions
  - Differences between string and cluster fragmentation in jet response
  - ATLAS: additional inclusive comparison of Pythia and Herwig in tt
  - Color reconnection model
- Others:
  - PDF, underlying events etc.



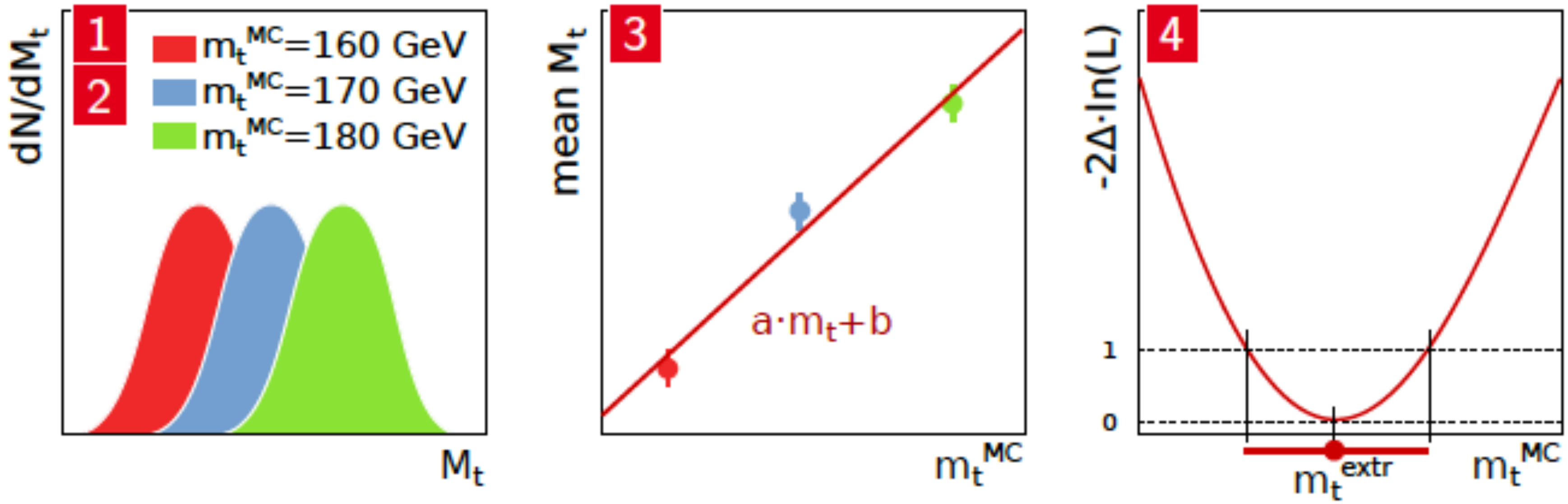
Measuring the top quark mass

- Jet energy scale is among leading systematic uncertainties
- JES calibrated using Z+jet and dijet events
- Use in-situ methods to determine jet scale factor (JSF) in top events
  - Often used: constrain light-quark JES from W boson mass
  - Absorbs flat parts of JES uncertainty. Remaining uncertainties from pT/η dependencies and differences between jet flavours (light/gluon vs. b)
    - ATLAS also determines a bJSF in addition to extraction of JSF
- ATLAS and CMS uncertainties quite similar at relevant <pT>
  - light jet <pT>~60 GeV; b-jet <pT>~80 GeV
- CMS flavor uncertainties for ttbar (here shown for QCD) similar to ATLAS
- Overall JES uncertainty for ttbar smaller at CMS



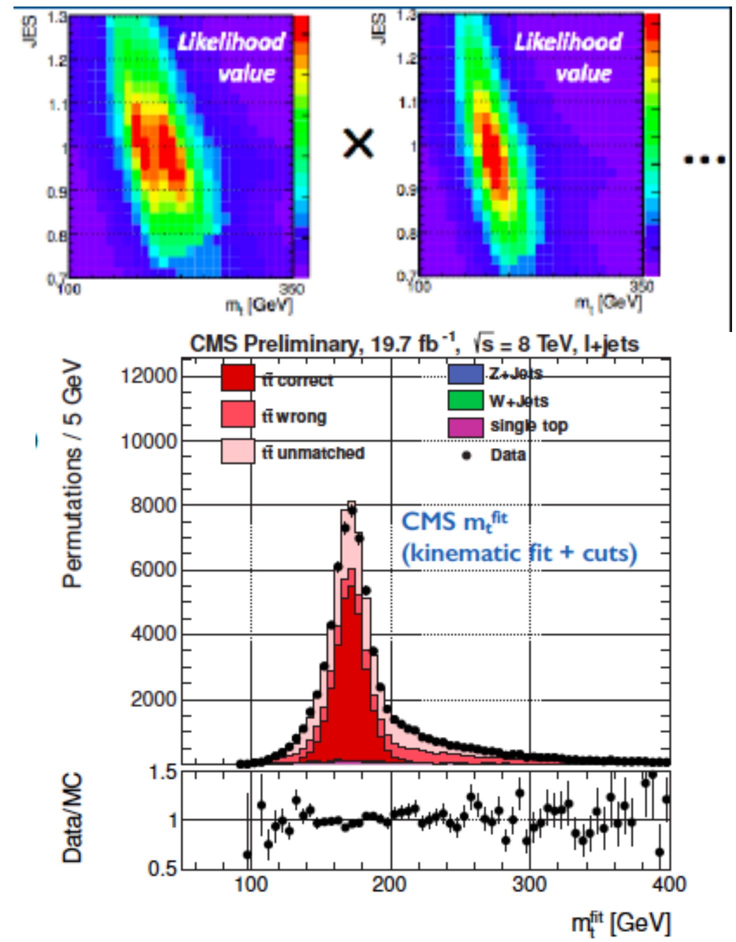
Method

1. Select ttbar candidate events
   - high integrated luminosity, efficient b-tag algorithms
2. Construct estimator M_t for top mass
3. Parametrize dN/dM_t in terms of m_t^{MC}
   - e.g. l+jets, alljets, template and ideogram methods used at LHC
4. Perform maximum likelihood fit
   - Calibrate on MC, evaluate on data, ttbar modeling very important



Lepton+jets

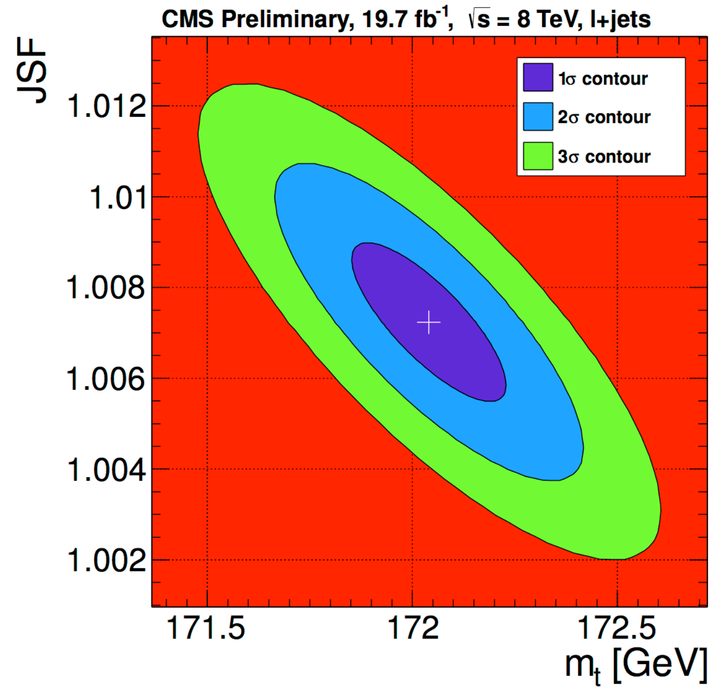
- Kinematic fit: constrain W mass, top-antitop masses
  - In-situ JES calibration
  - Goodness of fit
  - Event-by-event weight
  - 42% correct, 21% wrong, 37% unmatched
  - Also use info from incorrect assignments
- Kinematic fit + “ideogram” method
  - Combine event-per-event likelihood
  - Multiple permutations per event
  - Different templates for each permutation
  - Allows for in-situ calibration of the light quark JES from W→ qq’



CMS-PAS-TOP-14-001 (Mar '14)

Lepton+jets

- Kinematic fit + "ideogram" method
  - Combine event-per-event likelihood
  - $m_t^{fit} \leftrightarrow (m_t\ , \text{JSF})$; $m_W^{reco} \leftrightarrow \text{JSF}$



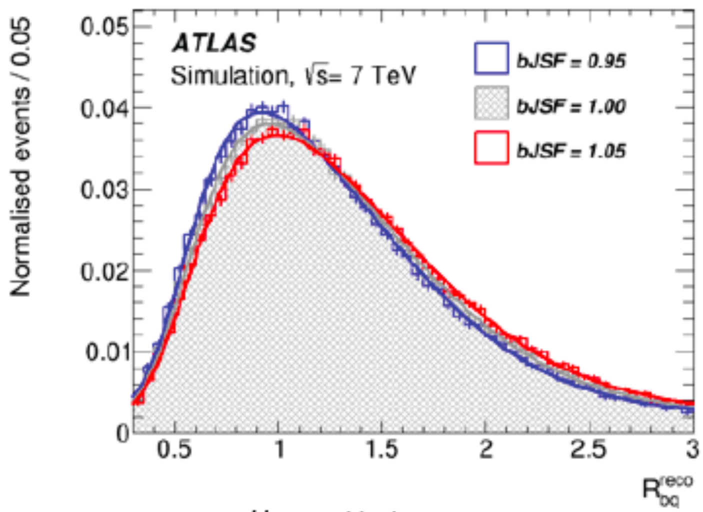
  - No single dominant systematic uncertainty
    - bJES (0.41), signal modelling (0.35 GeV)
    - JSF-1 = +0.7 ± 1.2% (syst.+stat.)
  - Most precise LHC result to date

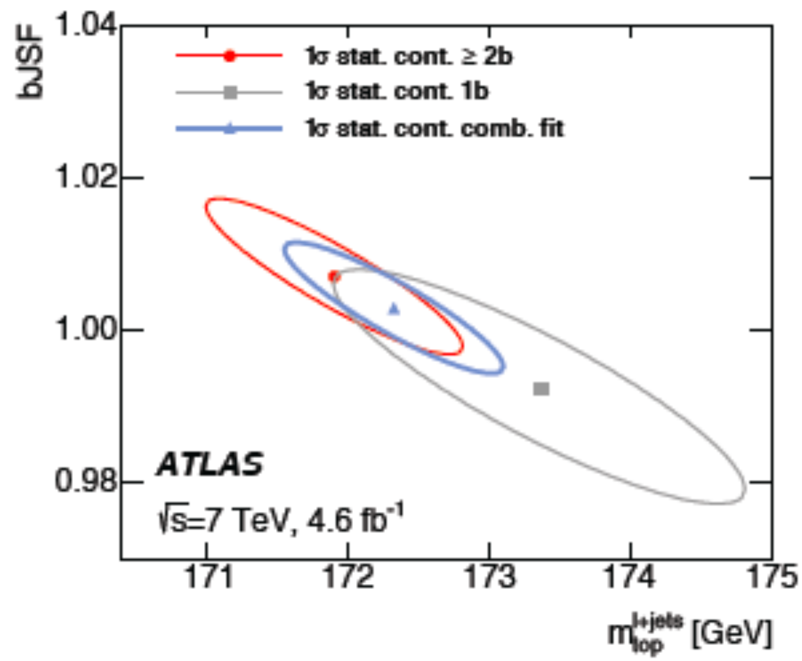
CMS 172.0 ± 0.2(stat) ± 0.8(syst) GeV

CMS-PAS-TOP-14-001 (Mar '14)

Lepton+jets

- Signature 2 b, lepton, 2 jet, MET (ν)
- Simultaneous fit of 3 observables : m_{top}^{reco}, m_W^{reco}, R_{bq}^{reco}
- Constraints both JSF (m_W) and bJSF ($R_{bq} \sim p_T^b / p_T^W$)
- R_{bq}^{reco} sensitive to relative b-to-light-jet energy scale



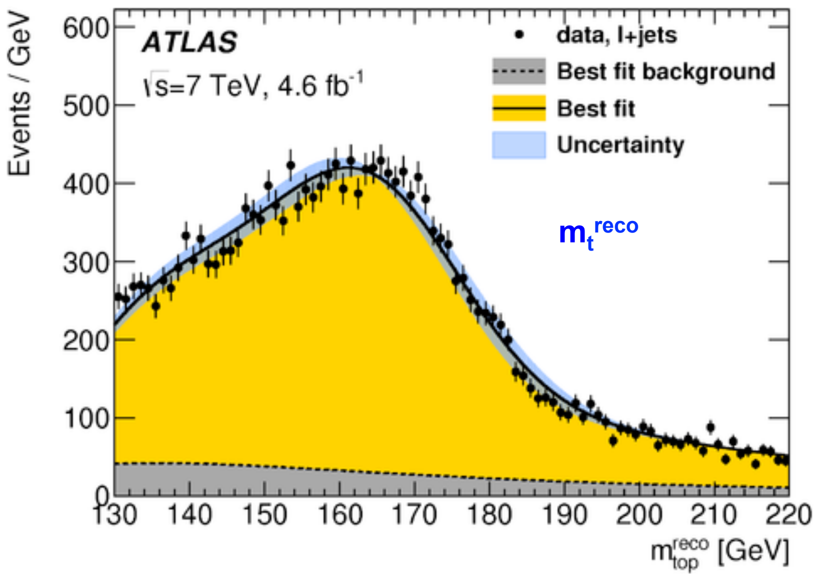


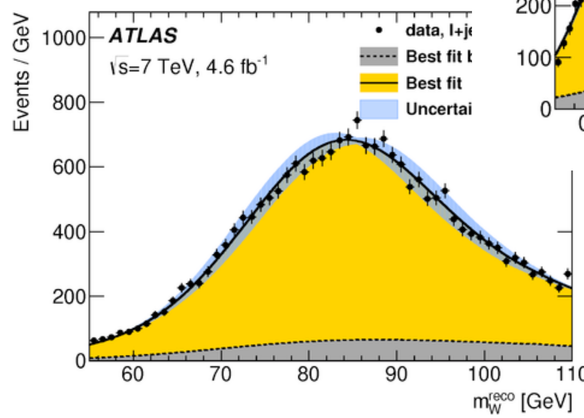
$$R_{lb}^{reco} = \frac{p_T^{blep} + p_T^{bhad}}{p_T^{W_{jet_1}} + p_T^{W_{jet_2}}} \quad \text{(2b-tagged jet events)}$$

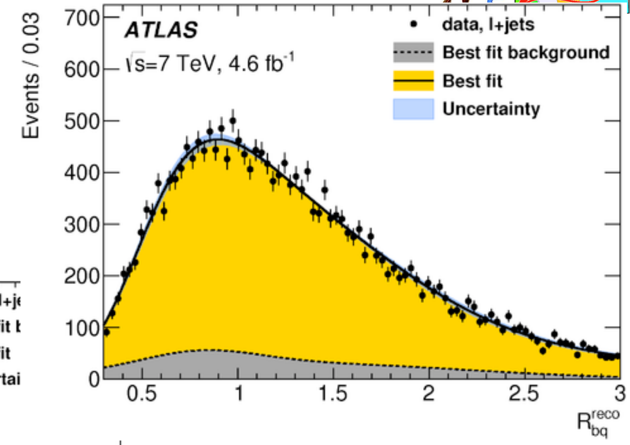
$$R_{lb}^{reco} = \frac{p_T^{btag}}{(p_T^{W_{jet_1}} + p_T^{W_{jet_2}})/2} \quad \text{(1b-tagged jet events)}$$

ATLAS arXiv:1503.05427 **(Mar '15)**

Lepton+jets







Blinded with a unknown constant offset (same as dileptons)

- 3D vs 2D analysis reduces syst. by ~40%
  - bJSF stat. (0.67); JES (0.58), b-tagging (0.50 GeV)
  - JSF-1 = +1.9 ± 2.7% (syst.+stat.)
  - bJSF-1 = +0.3 ± 2.4% (syst.+stat.)

ATLAS 172.3 ± 0.8(stat) ± 1.0(syst) GeV

ATLAS arXiv:1503.05427 (Mar '15

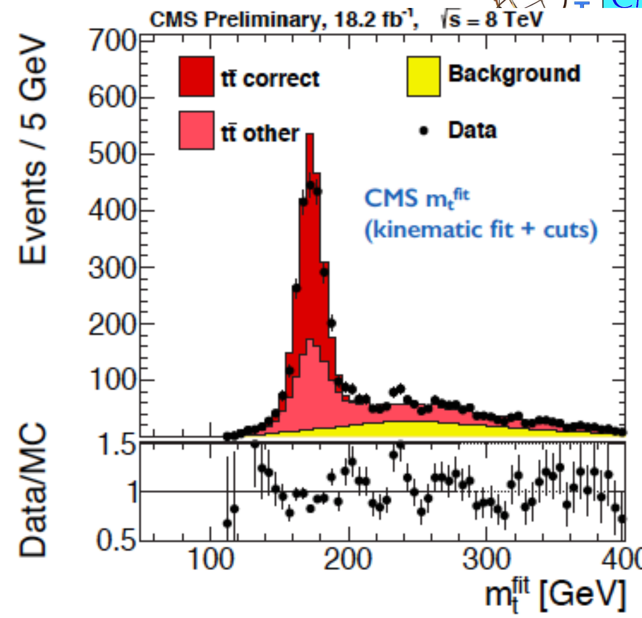
All jets

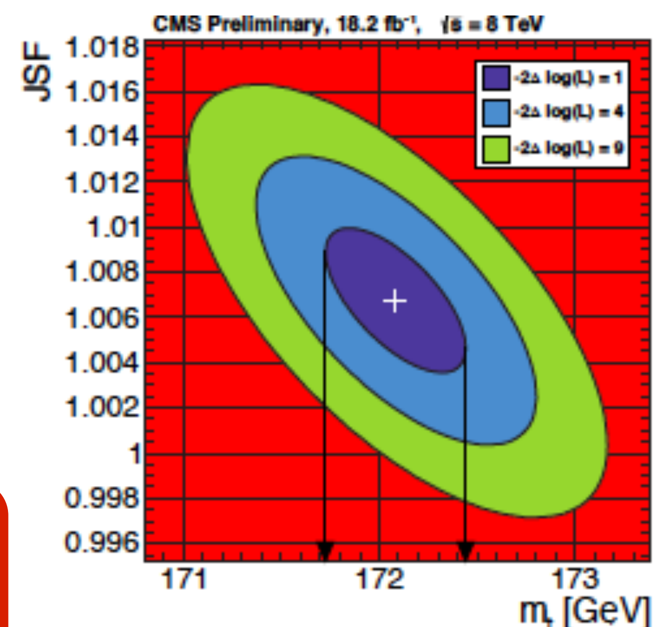
- Selected objects:
  - ≥4 light jets, 2 b-tagged jets
- Same ideogram methods as l+jet (2D fit)
  - Constrain light jet energies to m_W
  - Kinematic fit reconstruct top mass

$$\chi^2 = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}$$

    - Purity 78% with narrow signal peak
    - cut on goodness-of-fit χ^2+ $\Delta R(b,b)>2.0$
  - QCD multijet production is the only relevant background, data-driven estimate
  - Kinematic fit on zero-btag sample (negligible signal contamination)
- Dominant uncertainity:
  - bJES (0.36), signal modelling (0.29 GeV)
  - JSF-1 = +0.7 ± 1.1% (syst.+stat.)

CMS 172.1 ± 0.4(stat) ± 0.8(syst) GeV





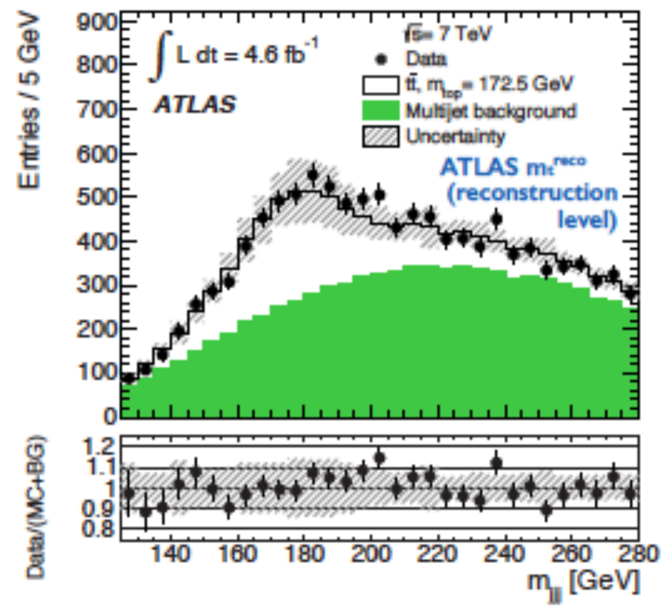
CMS-PAS-TOP-14-002 (Jul '14)

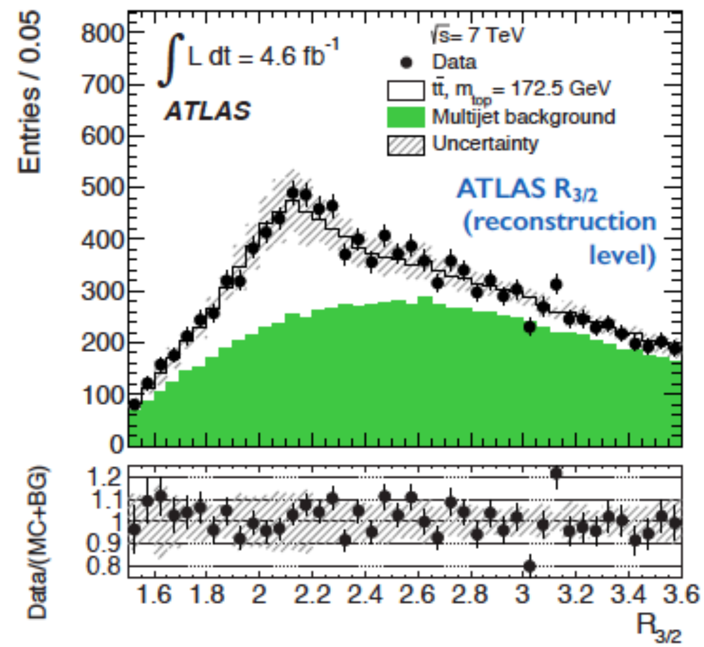
All jets

- m_t from template fit to
  - ratio of 3-jet mass to 2-jet mass

$$R_{3/2} = \frac{m_{top}^{reco}}{m_W^{reco}}$$

- Multijet background estimated from control regions in data
  - purity 17% similar to CMS (16%)
  - Divide into 6 regions by using two observables with minimal correlation: the number of b-tagged jets and the 6th jet pT
- Leading syst
  - bJES (0.61), JES (0.51),
  - Hadronization (0.50 GeV)



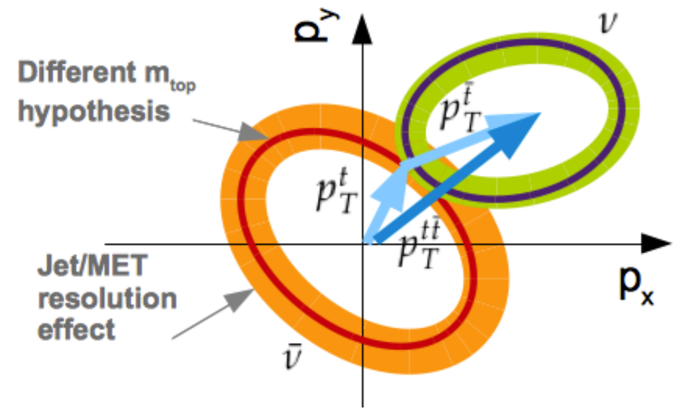


ATLAS 175.1 ± 1.4(stat) ± 1.2(syst) GeV

ATLAS, arXiv:1409.0832 (Sep '14)

Dilepton

- Signature: 2 b, 2 leptons, MET (2 ν)
  - under-constrained due to two ν
- A digression …
- 22 years or so ago, we did not think that we will be computing the top mass using dilepton events, until a striking e-mu event was observed!

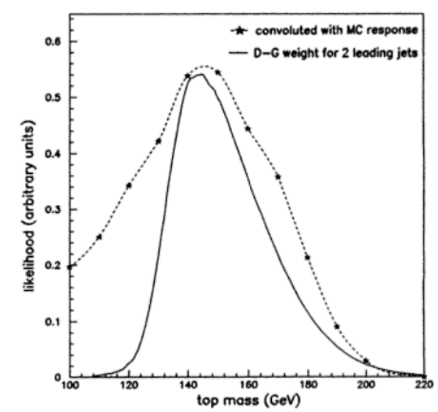


VOLUME 72, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1994

Search for the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s}$ =1.8 TeV

We have analyzed the surviving $e\mu$ event under the hypothesis that it is due to $t\bar{t} \to W(e\nu)W(\mu\nu)b\bar{b}$ using an extension of the likelihood method based solely on the event topology as described in Ref. [13]. Our analysis [14] shows that this event is kinematically consistent with $t\bar{t}$ production over the mass range 100 to 200 GeV/c^2. Using a likelihood function based upon the parton distribution functions, partonic cross sections, and decay lepton distributions, we find that the peak likelihood for this event is near the median found in MC top samples. The likelihood distribution is maximized for a top mass of about 145 GeV/c^2, but masses as high as 200 GeV/c^2 cannot be excluded. This result is consistent with, but independent of, our lower limit on m_t described above.

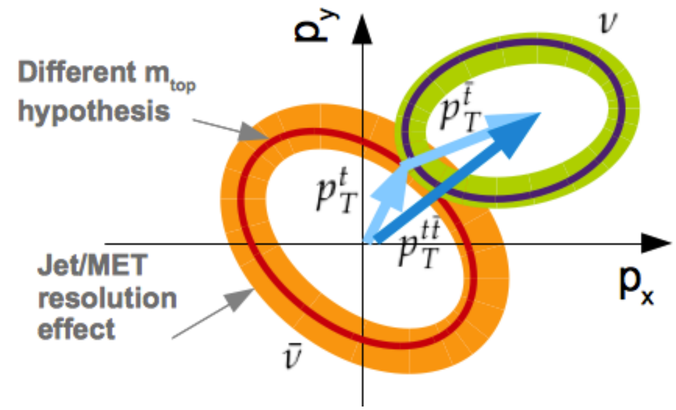
international europhysics conference, Marseille 1993

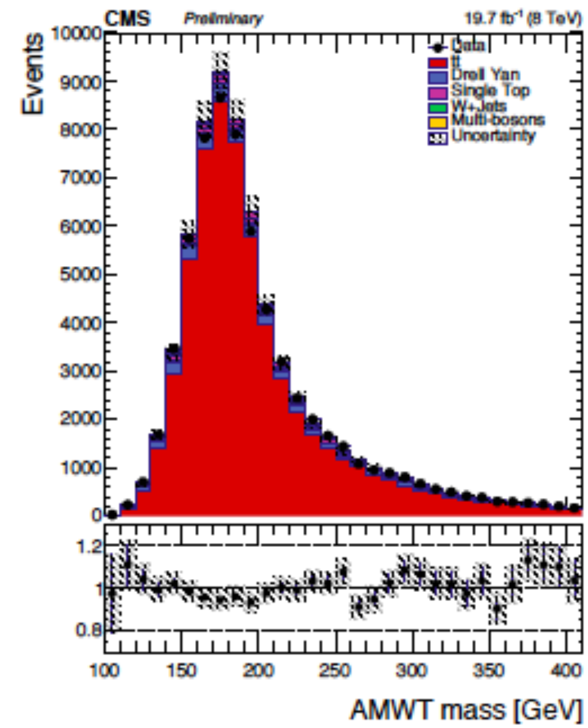


Dilepton

- Signature: 2 b, 2 leptons, MET (2 ν)
  - under-constrained due to two ν
- First **blind m_t measurement** from CMS
- Analytical Matrix Weighting Technique (AMWT)
  - Reconstruct most likely mass for the event
  - One degree of freedom in the kinematics
  - Up to 8 possible solutions per event
  - Scan m_t hypotheses
    - solve using smeared jets, assign ME weight
    - Highest weight → m_{reco}
- Leading systematics (in GeV):
  - JES (0.6), b frag. (0.7)
  - Renormalization and factorization scales (0.87)

CMS 172.5 ± 0.2(stat) ± 1.4(syst) GeV





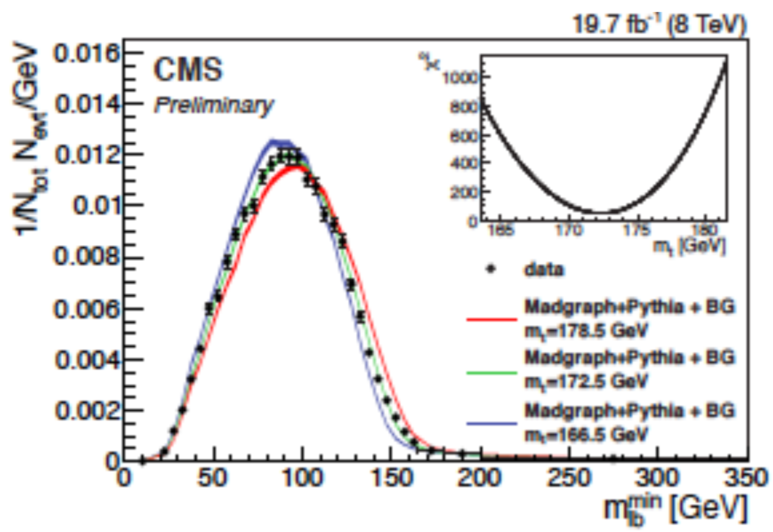
CMS-TOP-14-010 (Sep '14)

Dilepton

- Signature: 2 b, 2 leptons, MET (2 ν)
  - under-constrained due to two ν
  - eμ final state
- Invariant mass m_{lb} of lepton and b-jet
- Not sensitive to details of production mechanism or proton PDFs
- Reconstruct mlb and fit event
  - choose permutation that minimizes mlb
  - ~75-80% correct assignments
- Dominant uncertainties from normalization & background (in GeV):
  - JES (0.4), b frag. (0.6)
  - scale (0.55), top p_T (0.66)

$$\boxed{m_{lb}^2 = \frac{m_t^2 - m_W^2}{2}(1 - \cos\theta_{lb})}$$

$$\max(m_{lb}) \approx \sqrt{m_t^2 - m_W^2} \approx 153\text{GeV}$$

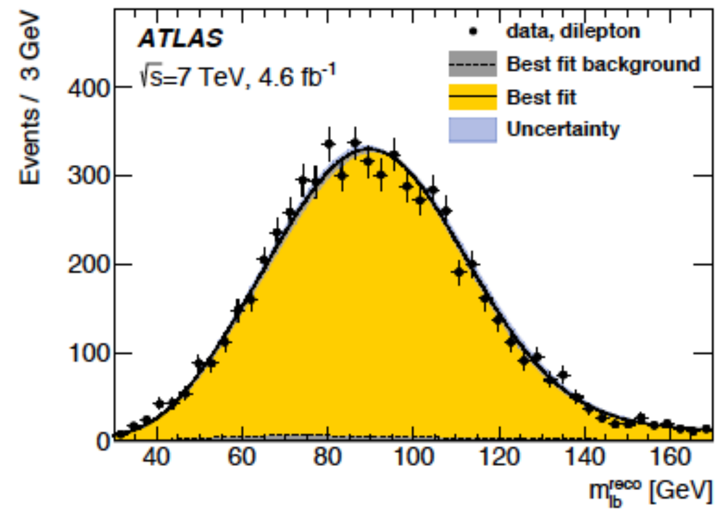


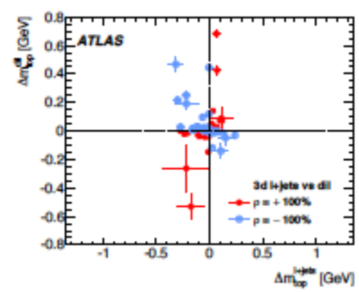
CMS 172.3 ± 0.3(stat) ± 1.3(syst) GeV

CMS-TOP-14-014 (Sep '14)

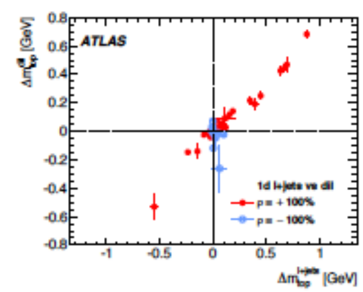
Dilepton

- Signature: 2 b, 2 leptons, MET (2 ν)
- Invariant mass m_{lb} of lepton and b-jet
- Dominant uncertainity:
  - JES (0.75), bJES (0.68),
  - Hadronization (0.53 GeV)
- Total uncertainty similar to CMS
  - Theory side strongly correlated
  - Larger JES (0.75 GeV vs 0.4–0.6 GeV)
  - Fewer events (7 TeV vs 8 TeV)
- In-depth study of correlations with l+jets
  - Reduces later combination uncertainty
- Blinded with a unknown constant offset (same as the lepton+jets)





(a) 3d ℓ+jets vs dilepton



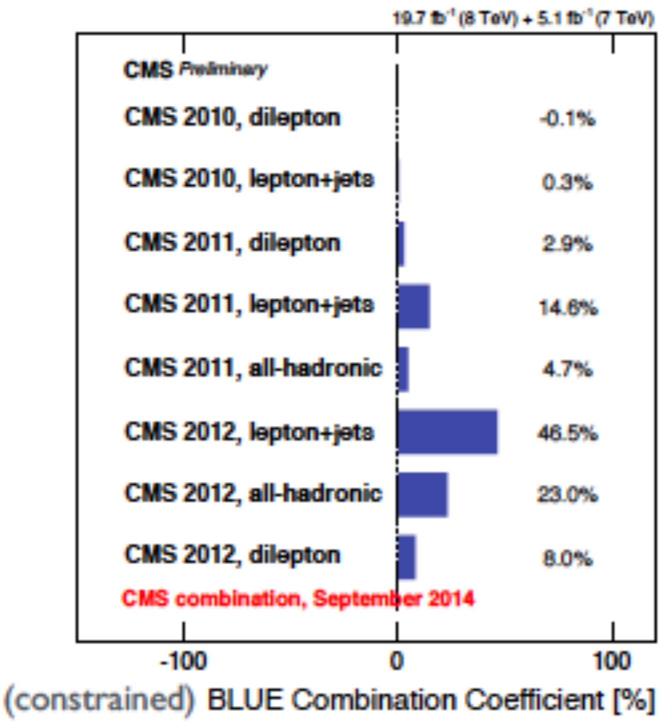
(c) 1d ℓ+jets vs dilepton

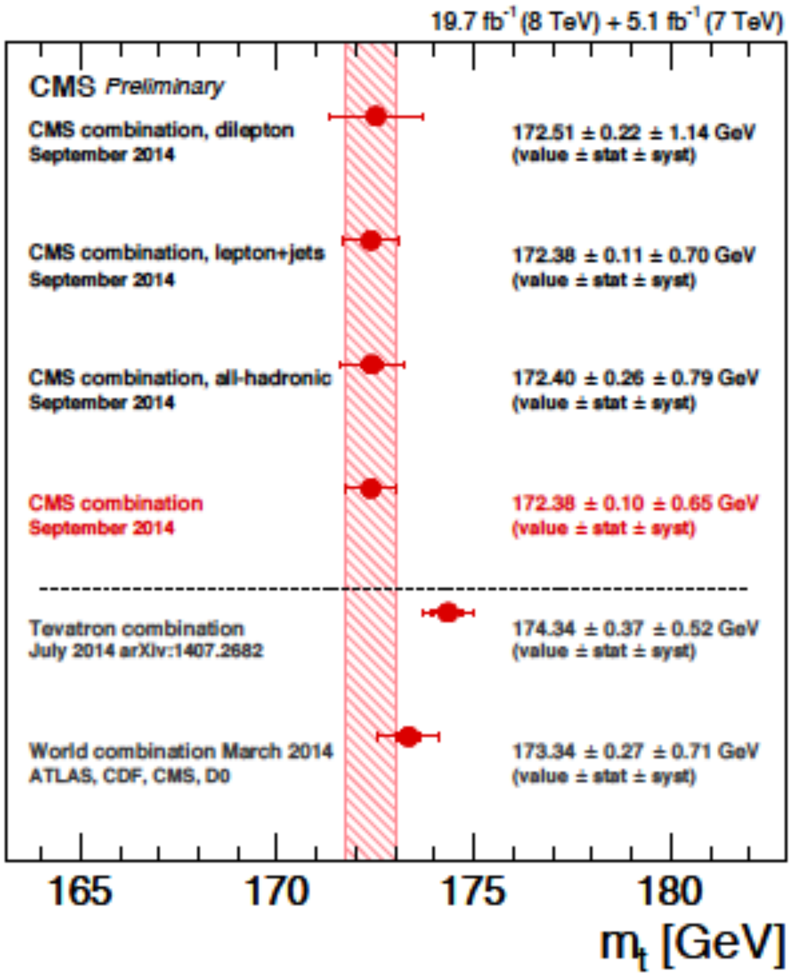
ATLAS: 173.8 ± 0.5(stat) ± 1.3(syst) GeV

ATLAS, arXiv:1503.05427 **(Mar '15)**

Top quark mass - CMS summary

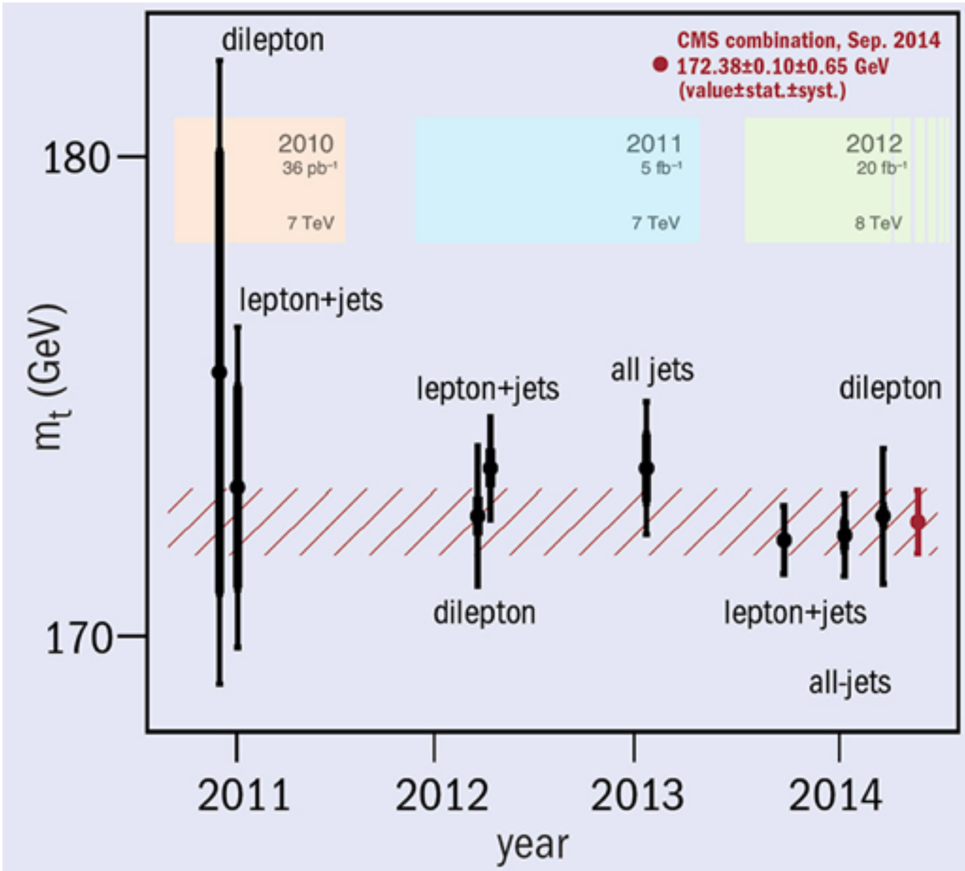
- Good consistency between individual measurements
- All 2011-2012 contribute
- Combination dominated by precise 2012 lepton+jets





CMS-PAS-TOP-14-015 (Sep '14)

Top quark mass - CMS summary

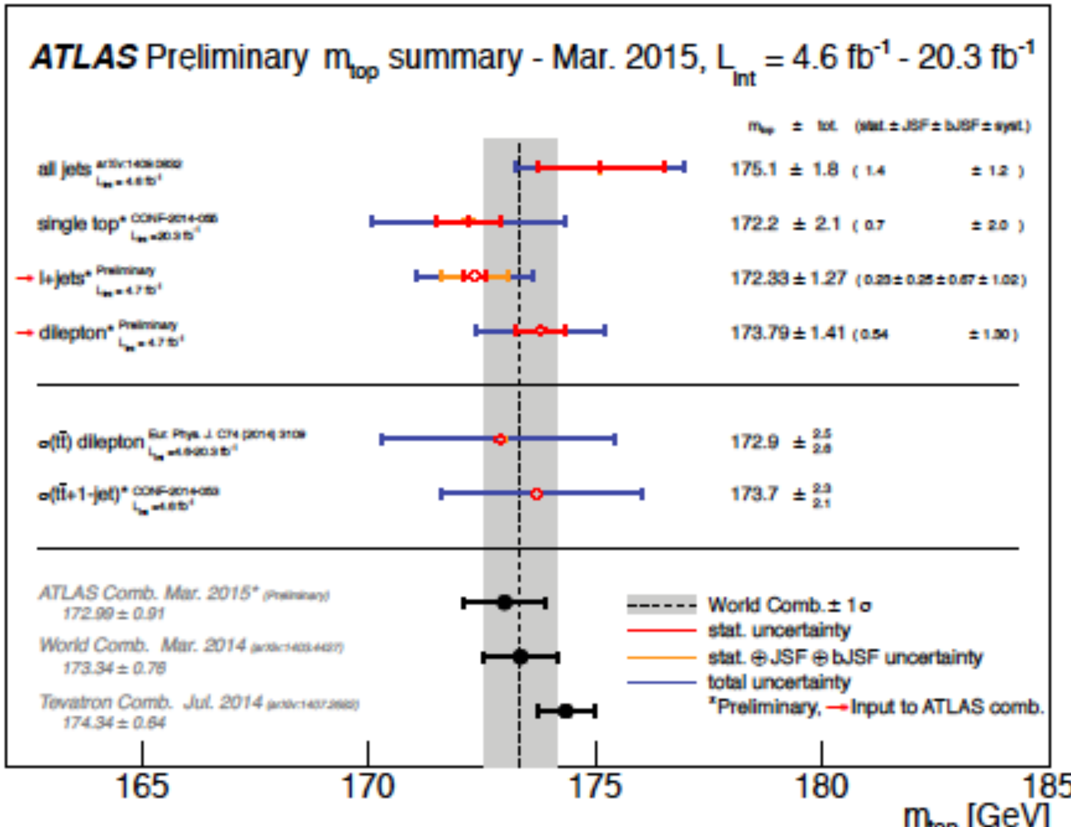


CMS: 172.4 ± 0.1(stat) ± 0.7(syst) GeV

CMS-PAS-TOP-14-015 (Sep '14)

Top quark mass - summary

- ATLAS combination using lepton+jet and dilepton channels



gain in precision:
- 28% relative to l+jet only,
- 36% relative to previous ATLAS combination

Combined systematics (Gev):
- JES (0.41), bJES (0.34)
- hadronization (0.35)
- b-tagging (0.25)

ATLAS: 173.0 ± 0.5(stat) ± 0.8(syst) GeV

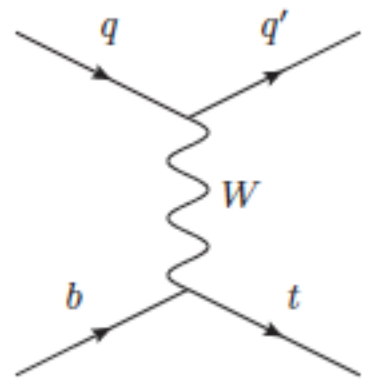
Alternate methods

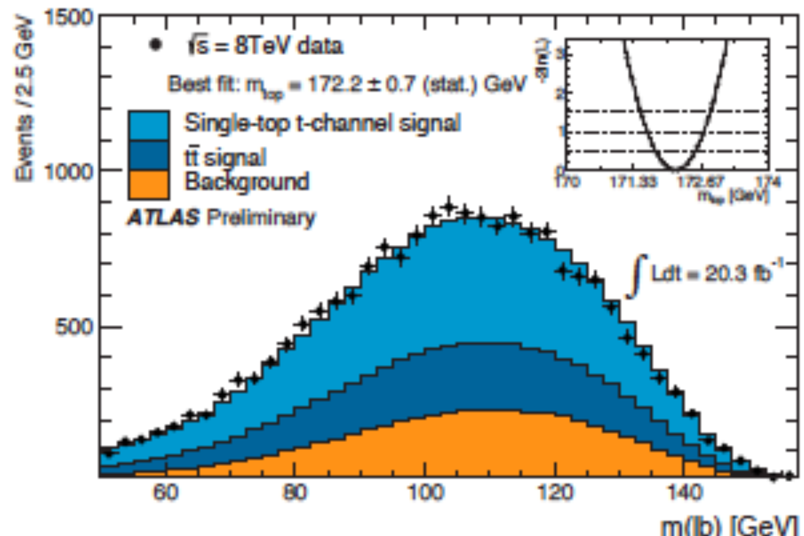
- Standard measurements:
  - tt event reconstruction
  - mass calibration based on MC: $m_t^{measured} = m_t^{MC}$
  - large sensitivity to JES (bJES) uncertainty

- Alternative methods (complementary)
  - observables/final states sensitive to different systematic uncertainties
  - extract top quark mass in well-defined renormalization scheme
- Methods explored:
  - B-hadron lifetime
  - Kinematic end points
  - Studies of b→J/ψ and underlying event
  - Single-top events in t-channel
  - tt cross section
  - tt+jet differential cross section

Single top t-channel

- Single top t-channel complementary to tt measurements
  - statistically independent sample
- 1 lepton + Missing ET + 1 b + 1 light jet
- Deploy neural network to obtain a sample with enriched t-channel contribution
- Use m_{lb} observable as estimator
- Template fit method to extract mass
- Different sensitivity to uncertainties:
  - Less combinatorial background, single v
  - Larger overall background level
  - Different color reconnection and different Q^2 scale
- Dominant uncertainties
  - JES (1.5 GeV)
  - hadronization (0.7 GeV)
  - backgrounds (0.6 GeV)



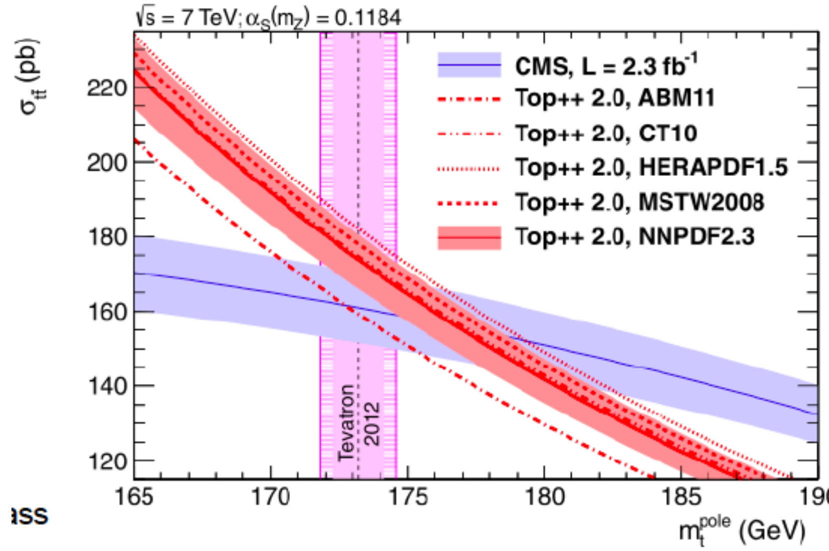


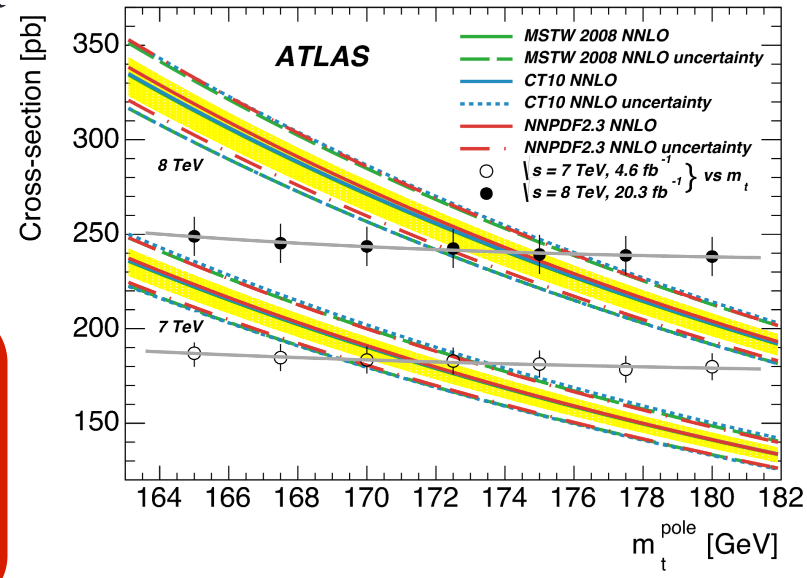
ATLAS:172.2 ± 0.7(stat) ± 2.0(syst) GeV

ATLAS-CONF-2014-055 (Sep '14)

Mass from tt cross section

- Extract mass from cross section
  - determine m_t^{pole} using the experimental ttbar production cross section
- Comparatively large systematics
  - dominant theory uncert. from PDF and scale
  - Biggest challenge is reducing theory uncertainty expect $\Delta(m_t^{MC}, m_t^{pole}) \lesssim 1$ GeV
- Extract mass for fixed α_S
- Results consistent with standard measurements and EWK fits
  - Constrain α_S at the scale of the Z boson mass and derive m_{top} pole
  - Constrain m_{top} pole to the measured value and derive α_S.





m_t^{pole}

ATLAS: = 172.9 ± 2.6 GeV (7 & 8 Tev)

CMS: m_t^{pole} = 176.7 ± 3.0 GeV (7 TeV)

EPJC74 (2014) 3109; PLB 728 (2014) 496 (Nov'14)

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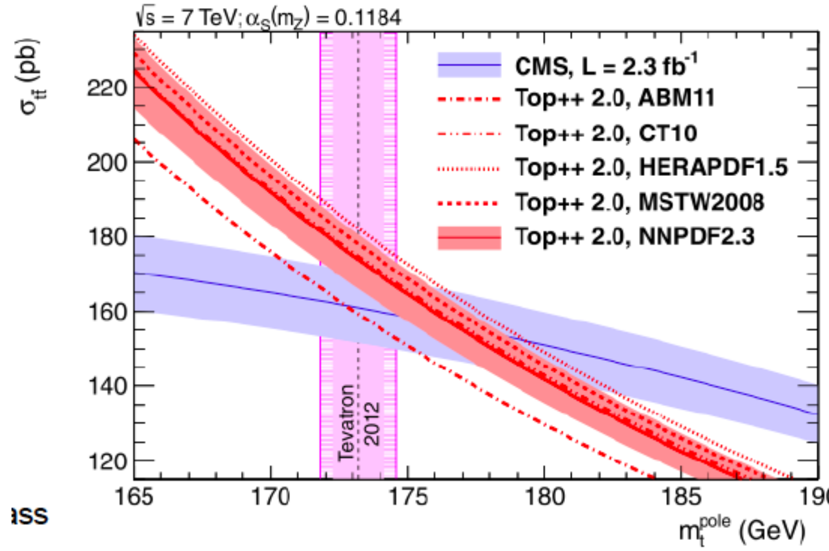
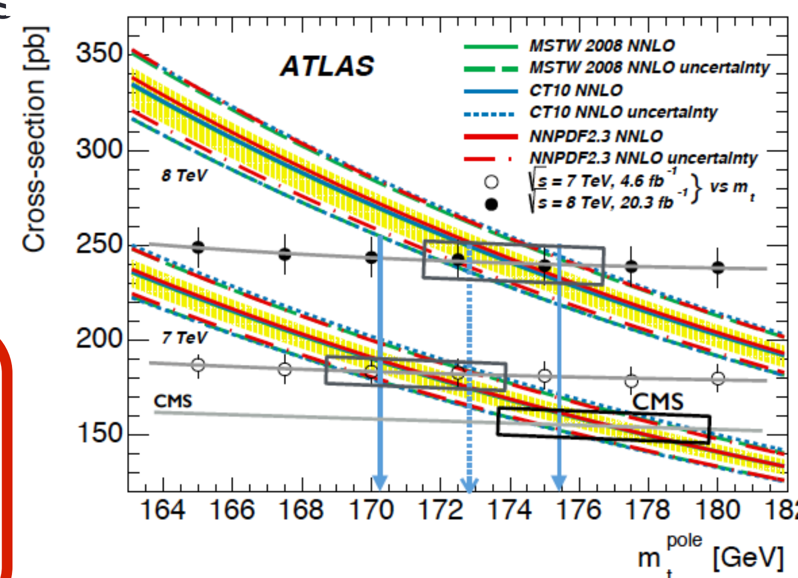
  - Constrain m_{top} pole to the measured value and derive α_S.





m_t^{pole}

ATLAS: = 172.9 ± 2.6 GeV (7 & 8 Tev)

CMS: m_t^{pole} = 176.7 ± 3.0 GeV (7 TeV)

EPJC74 (2014) 3109; PLB 728 (2014) 496 (Nov'14)

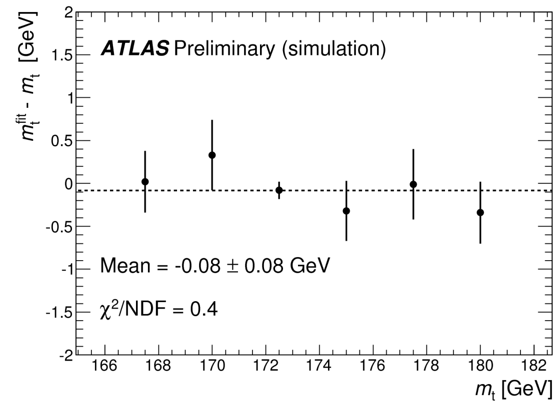
Mass from tt+1jet differential cross section

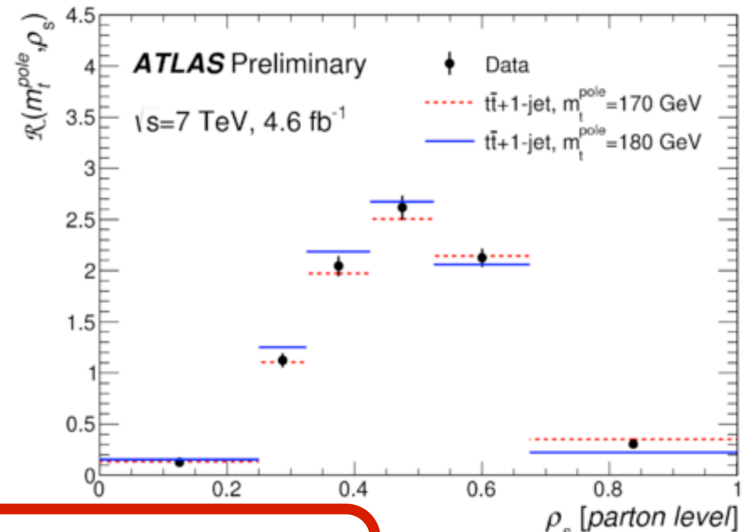
- Pole mass extracted from normalized differential cross section $R(m_t^{pole}, \rho_s)$ as a function of ρ_s (arXiv: 1303.6415)

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s),$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}},$$

$\sqrt{s_{ttj}}$= invariant mass of tt +1-jet system and $m_0 = 170$ GeV





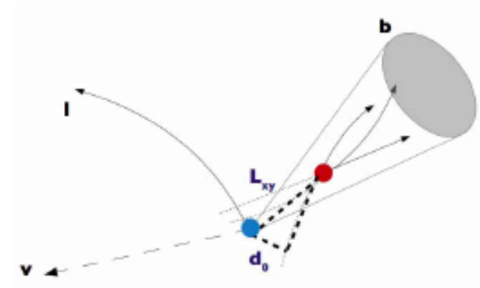
- Theoretical differential distribution calculated at parton level (NLO+PS)
- Dominant systematics : JES, ISR/FSR, PDF
- Dominant theory uncertainty (NLO+PS calculation) : scale uncertainty
- Will benefit from 8 TeV increased statistic

ATLAS: 173.7 ± 1.5(stat) ± 1.4(syst)$^{+1.0}_{-0.5}$(th.) GeV

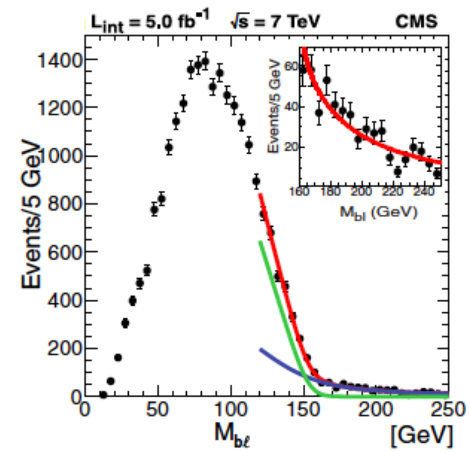
ATLAS-CONF-2014-053 (Sep '14)

Other alternate method

- B-hadron lifetime
  - (CMS-PAS-TOP-12-030, FTR-13-007)
  - b quark p_T is proportional to m_t (and $p_{T,t}$)
  - B hadron carries most of initial b quark p_T
  - Almost no sensitivity to JES

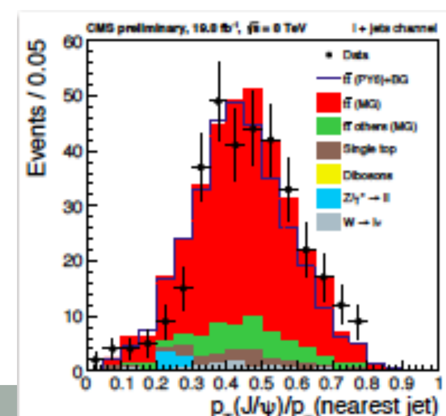


- Kinematic end points
  - (EPJC 73 (2013) 2494, FTR-13-007)
  - Sensitive to decaying particle mass
  - dominant uncertainty bJES



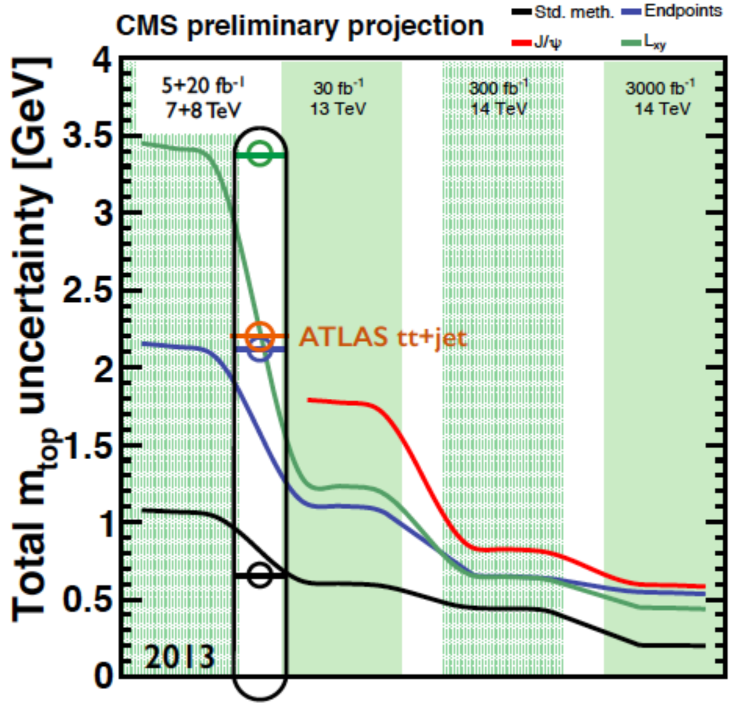
- J/ψ Method:
  - (FTR-13-007)
  - The invariant mass of a J/ψ from the b-jet together with the lepton from the W decay as observable.

- Studies of b→J/ψ and underlying event
  - (CMS-PAS-TOP-13-007)
  - Rare processes, B→J/ψ+X→$\mu^+\mu^-$+X, very clean signal
  - Challenge large sensitivity to b fragmentation

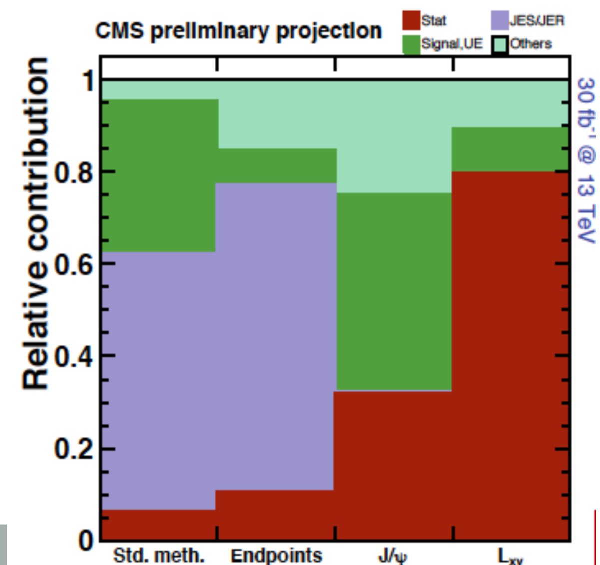


Future Projections

- Might be able to measure m_{top} with a precision of 200 MeV
- Large drop in m_t uncertainties expected with Run II data
  - CMS: on track with standard methods using detailed m_t kinematics and demo of bJES from Z+b/Z+jet
  - ATLAS: promise for m_t^{pole} from differential σ_{tt}+1 jet and for m_t^{MC} with bJES from 3D method
  - ATLAS / CMS agreement on JES correlations
    - CMS-PAS-JME-14-003 / ATLAS-PHYS-PUB-2014-020
- Differential study of m_{top}
- Differential cross sections with full NLO tools
- No truly dominant systematic uncertainty
- b-fragmentation studies
  - Measure in-situ in ttbar events
- Interpretation will require improvement in understanding the theory

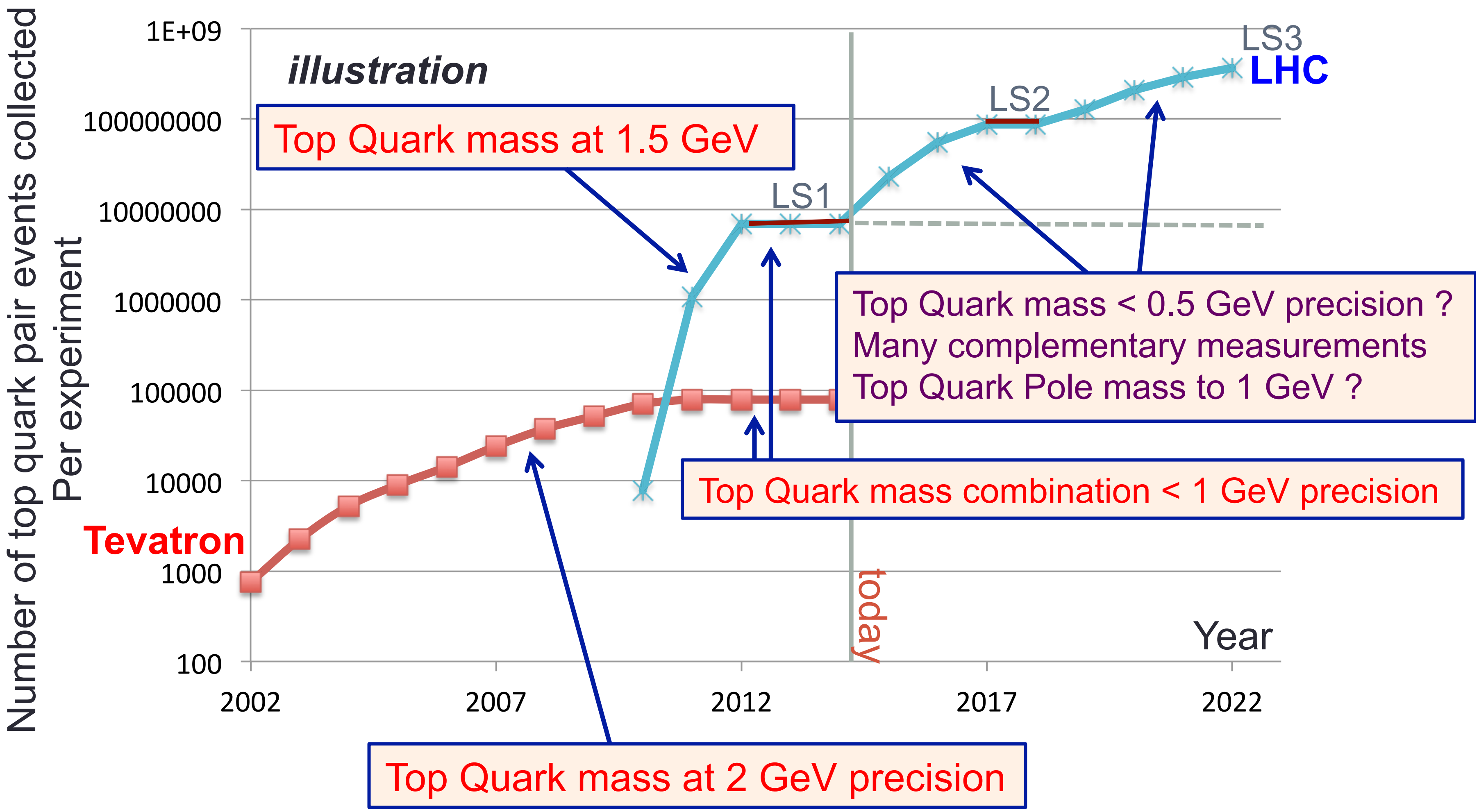


today 2015



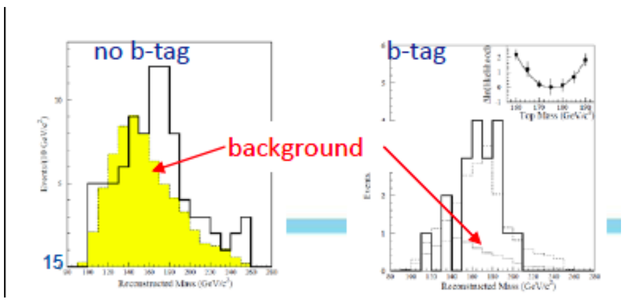
CMS-PAS-FTR-13-007

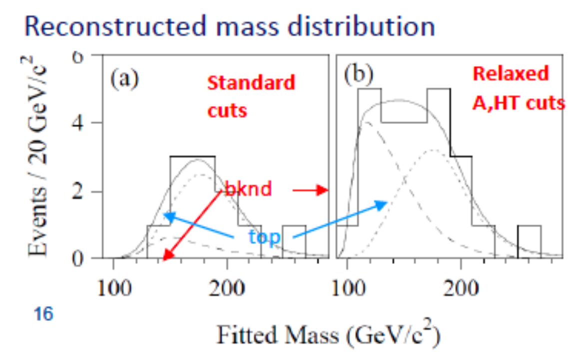
Conclusion: Status of Top Quark Mass



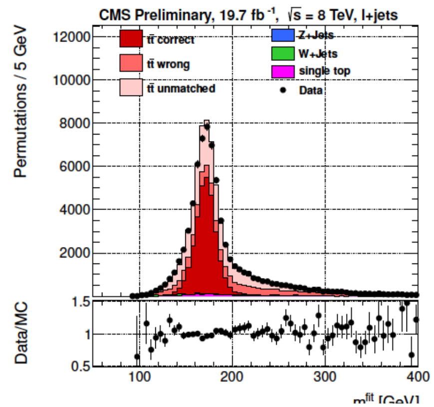
Conclusion: Status of Top Quark Mass

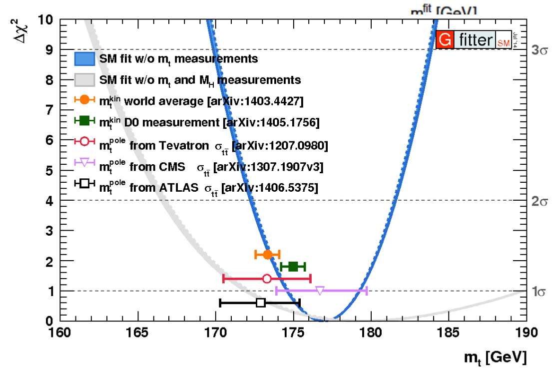
From 1995





To 2015





And BEYOND!

THANK YOU

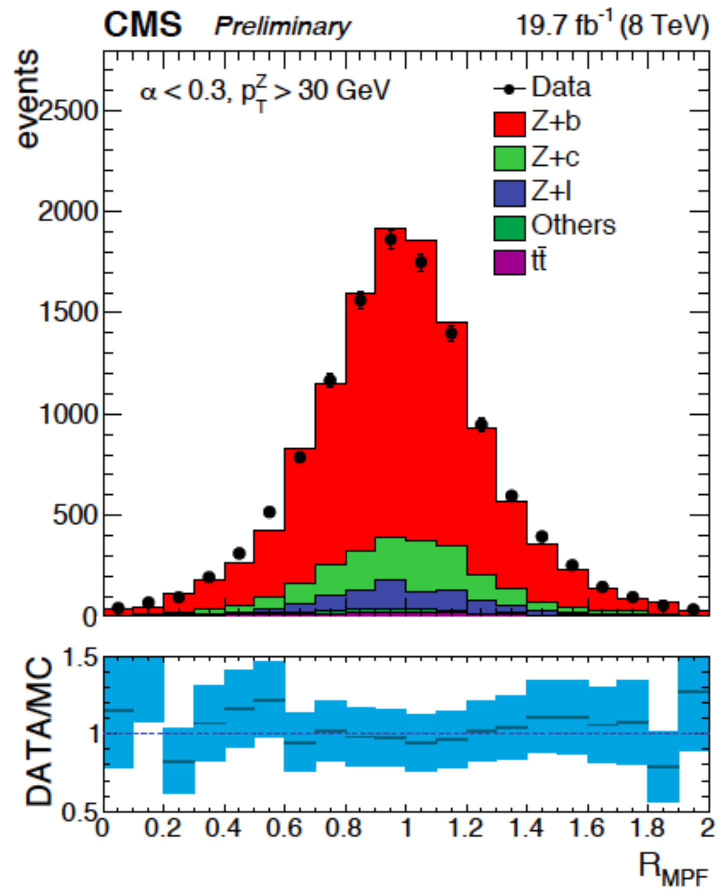
Thank You

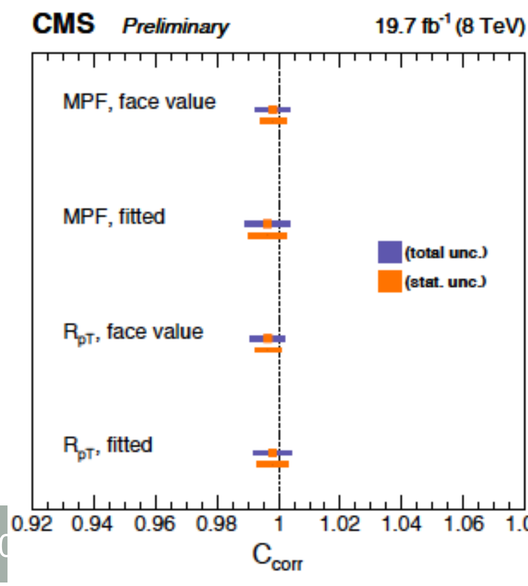
- The ATLAS and CMS collaborations

- Speakers at recent conferences,
  - whose slides I have heavily derived from

an aside: Z+b / Z+jet

- constraining dominant systematics
- bJES uncertainty large in most methods
  - even alternatives check p_T,B-hadron/p_T,b-jet in data
  - ATLAS 3D bJES: 0.08(syst) ± 0.67(stat) GeV
- Z+b kinematics close to W+b
  - "almost in-situ": complementary to 3D bJSF
  - precision on par with Pythia6-vs-Herwig and 3D
- Most systematics cancel for Z+b / Z+jet
  - many remaining shared with b from W+b, *e.g.*
  - neutrinos from semileptonic decays (0.32%)





bJES-1 (Pythia6) =
-0.2 ± 0.4(stat) ± 0.4(syst) %